AFFDL-TM-74-124-FXN

AIR FORCE FLIGHT DYNAMICS LABORATORY
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ENTHALPY MEASUREMENTS IN THE RENT FACILITY USING THE AEDC TRANSIENT ENTHALPY PROBE

Hudson L. Conley, Jr.

May 1974

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FOREWORD

This Technical Memorandum presents results of measurements taken in the RENT Facility using an enthalpy probe developed by AEDC. The AEDC probe is a fast response transient probe and was used in a swept mode giving profiles of local stagnation enthalpy. Six profiles were obtained with the facility configured to give "flat" profiles at a stagnation pressure of 1500 psi and arc current at 2600 amps and nine profiles were obtained with the facility configured to give "peaked" profiles at stagnation pressures ranging from 750 to 1800 psi and arc current at 2600 amps.

This report was prepared by Hudson L. Conley, Jr. of the Experimental Engineering Branch, Flight Mechanics Division as part of the Air Force Flight Dynamics Laboratory in-house research under Project 1426, "Aerodynamic Ground Test Technology", Task Number 142601, Work Unit 14260122, "Performance Evaluation of the AEDC Probe in Measuring Local Enthalpy in Aerospace Vehicle Re-Entry Test Facilities", and covers work conducted between July and December 1973.

The author wishes to thank Messrs. R. T. Smith and T. Giltinan of ARO, Inc. for their cooperation and assistance throughout this effort.

The author wishes to acknowledge the invaluable assistance of Elona Beans, who typed the drafts and final manuscript, and Airman First Class Robert M. Bishop, who prepared the figures.

This Technical Memorandum has been reviewed and is approved.

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INTRODUCTION

The heat transfer rates experienced by models in the Re-Entry Nose Tip (RENT) Leg of the Air Force Flight Dynamics Laboratory (AFFDL) 50 Megawatt (MW) Facility are significantly higher than that predicted by stagnation point heating theory,[1,2] if the bulk (heat balance) enthalpy is used. This could be a result of (1) some of the assumptions in the stagnation point heating theories (i.e., laminar flow, equilibrium air, Newtonian pressure distribution around stagnation point) being violated, (2) a stagnation enthalpy distribution, (3) a stagnation pressure distribution in the free stream, or (4) any combination of these.

Null point calorimeters have been used in the past to measure stagnation point heating rate on hemispherical quarter inch nose radius models. It was found[3] that the stagnation point heating rate is a function of both radial position and time which indicates that there exist radial gradients as well as timewise fluctuations in free stream properties. Measurements[3] to date indicate that local stagnation pressure does not vary significantly either spatially or with time within the free stream core and hence, does not appear to be the primary cause of the stagnation point heating fluctuations and profile shapes. Hence, there is a need to make independent measurements of stagnation enthalpy profiles and fluctuations to determine their relationship to the measured stagnation point heating rates.

A RENT flow calibration test series was conducted from 3 to 19 October 1973 for the purpose of comparing and evaluating several techniques of determining local stagnation enthalpy. The techniques employed include: (1) two transient enthalpy probes, one developed by CALSPAN and the other developed by

Arnold Engineering Development Center (AEDC), (2) a copper line intensity ratio technique, being developed in-house, and (3) the null point calorimeter, where stagnation enthalpy is inferred from measurements of stagnation point heat transfer rate and pressure.

The purpose of this report is to present results of the measurements made with the AEDC probe during this flow calibration test series.

<u>BASIC THEORY OF THE TRANSIENT PROBE</u>

The AEDC transient total enthalpy probe is of the aspirating calorimetric type designed to operate in a swept mode to give an enthalpy profile. A schematic of this type of probe is shown in Figure 1. The probe works on the principle that energy from the aspirated gas is transferred to the tube, increasing tube temperature. The rate of rise in average tube temperature is related to the rate of increase of thermal energy in the tube by:

$$\frac{dH_{tube}}{dt} = \rho C_p V \frac{dT_{ave}}{dt} \tag{1}$$

where ρ and C_p are the density and specific heat of the tube material respectively, V is the volume of tube material, and dT_{ave}/dt represents the instantaneous time rate of change of the average temperature of the tube. The rate at which the tube is gaining energy must be equal to the rate at which the aspirating gas is losing energy. If a steady state assumption can be made for any given instant in time, the rate of energy loss by the gas can be represented by:

$$\frac{dH_{gas}}{dt} = (H_o - H_e)\dot{m} \tag{2}$$

where H_o and H_e are the total enthalpy of the gas at the entrance to the tube (stagnation enthalpy) and the total enthalpy of the gas at the exit of the tube (residual enthalpy) respectively and $\dot{m}$ is the mass flow rate of the aspirated gas. If by the time it has reached the tube exit, the gas is cooled enough that an accurate measurement of its total temperature can be made, the residual total enthalpy can be determined by:

$$H_e = C_{p_g} T_e \tag{3}$$

where C_{p_g} is the specific heat of the gas and T_e its total temperature at the tube exit.

Equating equations (1) and (2) and using equation (3), the stagnation enthalpy is given by:

$$H_o = \frac{\rho V C_p}{\dot{m}} \frac{dT_{ave}}{dt} + C_{p_g} T_e \qquad (4)$$

It has been shown(4) that if the electrical resistivity of the tube material varies linearly with temperature and a constant current is put through the aspirating tube, the instantaneous change in average tube temperature with time is related to the time rate of change of voltage across the tube by:

$$\frac{dT_{ave}}{dt} = \frac{1}{\alpha R_o I} \frac{dV}{dt} \qquad (5)$$

where α is the coefficient of electrical resistivity of the tube material, R_o is the tube's electrical resistance at a reference temperature, I is the current through the tube, and dV/dt is the instantaneous time rate of change of voltage across the tube. The equation for total enthalpy can now be written as:

$$H_o = \frac{\rho V C_p}{\dot{m}} \frac{1}{\alpha R_o I} \frac{dV}{dt} + C_{p_g} T_e \qquad (6)$$

Equation (6) is the basic form of the data reduction equation in that all quantities on the right hand side of the equation can be measured or are known basic properties of the tube material or the aspirated gas.

DESCRIPTION OF AEDC PROBE

The author of this report was not involved in the actual development of the AEDC probe, therefore only a brief description of the particular model, designated C-4, used in the RENT flow calibration test series will be given. Reference 5 contains some background on the development and evolution of the probe. Further details were presented by Pigott, Smith, and MacDermott at the 37th Semiannual Meeting at the Supersonic Tunnel Association (STA).

A sketch of the essential features of the probe is shown in Figure 2. The test gas is aspirated through the platinum tube into a small volume used as a stilling chamber for the mass flow measuring orifice located in the side of the volume. The pressure (P_{or}) in the small volume is measured with a piezoelectric transducer and the temperature (T_e) of the gas in the volume is measured with a thermocouple. The mass flow rate of aspirated gas can then be determined by:

$$\dot{m} = K\frac{P_{or}}{\sqrt{T_e}} \qquad (7)$$

where K is a calibration constant. A known current is put through the aspirating tube and the voltage across the tube is measured through a bridge network. This signal is then fed through a differentiation circuit so that instantaneous values of dV/dt are measured directly.

Concurrently with the actual probe development, AEDC has developed data reduction techniques[5] that go beyond the simplified theory that is expressed in Equation (6) in that correction terms are added which take into account (1) heat losses from the aspirating tube to the surrounding probe structure.

(2) response time of the mass flow measurements, and (3) non-linear electrical resistivity - temperature relationship.

The raw data from the RENT series was reduced by AEDC[6] using both Equation (6) and Equation (6) plus the correction terms. The test conditions and results are presented in the next section.

TEST CONDITIONS AND RESULTS

The RENT (Re-Entry Nose Tip) Leg of the AFFDL 50 MW Facility is a high pressure, high enthalpy, continuous arc heated wind tunnel.[7,8] All tests were conducted using a nozzle with a 1.11 inch exit diameter and 0.9 inch throat diameter with the tip of the enthalpy probe positioned 0.1 inch from the exit plane. This nozzle is used for the majority of ablation testing in the RENT. Probe data was recorded every millisecond using the ambilog data system.

The flow calibration test series consisted of two distinct phases. The first phase consisted of six runs all at the same nominal stagnation pressure (100 atmospheres) and arc current (2600 amps) and with the swirl jets in a low swirl configuration. Experience has shown that with the swirl jets in this configuration the stagnation point heating profile is relatively flat. The actual conditions for each run along with the probe's sweep speeds are given in Table I. The measured enthalpy profiles are shown in Figure 3a through 3f. Both the uncorrected (Equation 6) and corrected (Equation 6 plus correction terms) data are presented for each run.

The second phase consisted of ten runs all at a nominal arc current of 2600 amps with two runs at each of the following nominal pressures; 750, 900, 1100, 1500, and 1800 psi. In this phase the swirl jets were in a high swirl configuration which has been shown[3] to give a peaked stagnation point heating profile. The actual conditions for each run along with the probe's sweep speeds are given in Table II. The results from these runs are presented in Figures 4a through 4i.

DISCUSSION

Since the primary purpose of this report is to present the results of some measurements taken in the RENT Facility and not to evaluate the probe, no attempt at determining its accuracy will be made at this time. It should be mentioned that not enough high speed data recording channels were available during the tests so that some of the probe parameters needed for the second order corrections were estimated rather than measured. Also, the residual gas thermocouple was lost on Run 070 and the residual gas temperature was estimated from previous data for this run and the two subsequent runs. Arguments for the existence of timewise fluctuations are made in Reference 3 and for this reason, even within the accuracy of the measuring technique, the data presented should not be thought of as representative enthalpy profiles for the given reservoir and heater conditions.

As far as measurements of local enthalpy in the RENT Facility are concerned, the AEDC probe is quite encouraging in that:

(1) The response time of the probe appears to be adequate for all test conditions and sweep speeds required for probe survival.

(2) The measured values of enthalpy and the profile shapes appear reasonable.

(3) An upgrading of the data acquisition system in the 50 MW Facility is under way which will provide a sufficient number of high speed data channels so that in the future all probe parameters necessary for the most accurate operation of the probe can be recorded.

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RUN NUMBER	P_o (PSI)	ARC CURRENT (AMPS)	HEAT BALANCE (BTU/LBM)	SWEEP SPEED (IN/SEC)
057	1514	2620	1850	49.4
058	1500	2580	1910	47.9
059	1510	2595	1800	48.2
060	1500	2615	1950	45.4
061	1520	2600	1920	47.9
062	1510	2612	1800	47.2

TABLE I

TEST CONDITIONS AND PROBE SWEEP SPEED FOR FIRST PHASE OF FLOW CALIBRATION TEST SERIES

RUN NUMBER	P_o (PSI)	ARC CURRENT (AMPS)	HEAT BALANCE (BTU/LBM)	SWEEP SPEED (IN/SEC)
063	768	2626	2140	53.4
064	770	2590	NOT RECORDED	57.4
*065	903	2632	2050	64.0
066	900	2596	2040	64.7
067	1093	2620	1910	68.4
068	1100	2589	NOT RECORDED	68.8
069	1492	2594	NOT RECORDED	69.9
070	1496	2609	2170	71.1
071	1805	2684	2320	87.3
072	1789	2603	2200	89.1

TABLE II

TEST CONDITIONS AND PROBE SWEEP SPEED FOR SECOND PHASE OF FLOW CALIBRATION TEST SERIES

* Probe data for this run was unusable due to an electrical ground loop in the probe

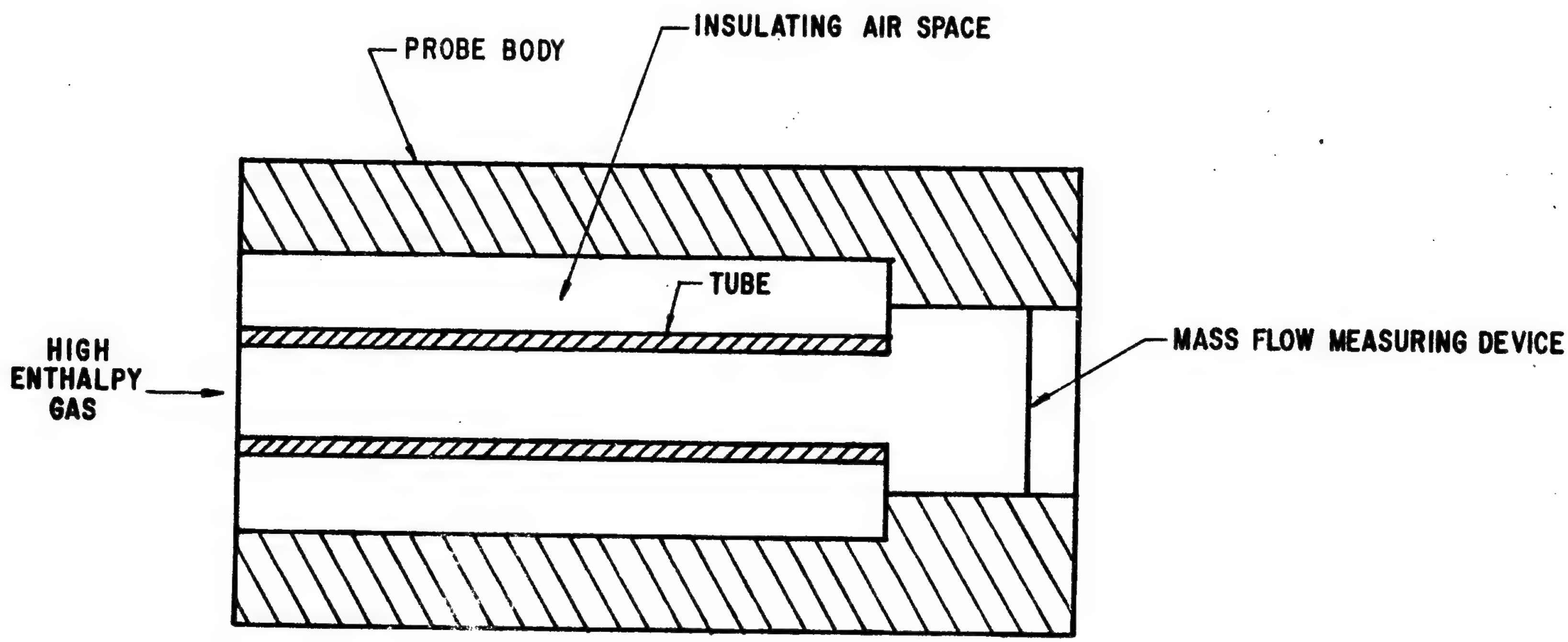

Figure 1. SCHEMATIC of TRANSIENT ENTHALPY PROBE

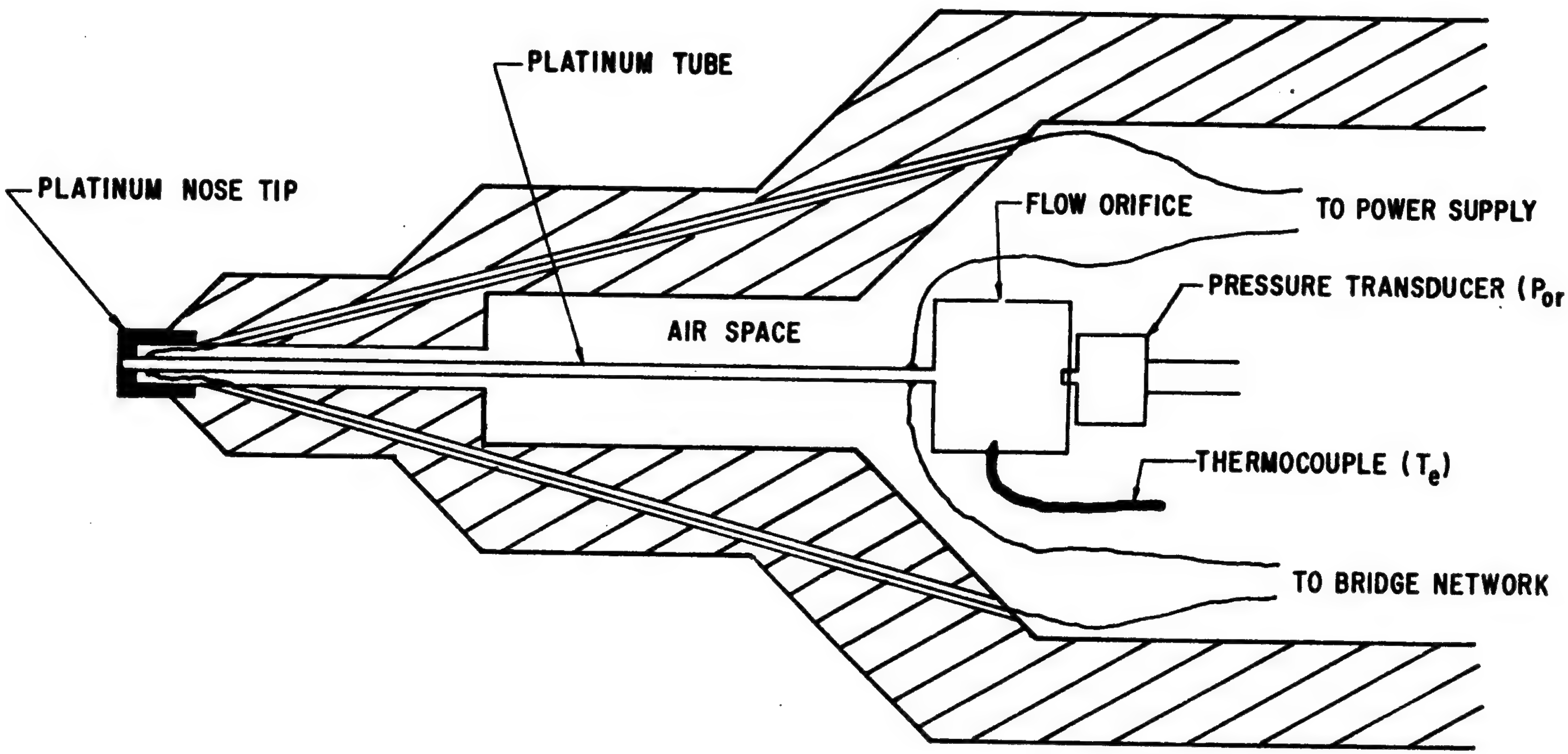

Figure 2. SKETCH of AEDC C_4 ENTHALPY PROBE

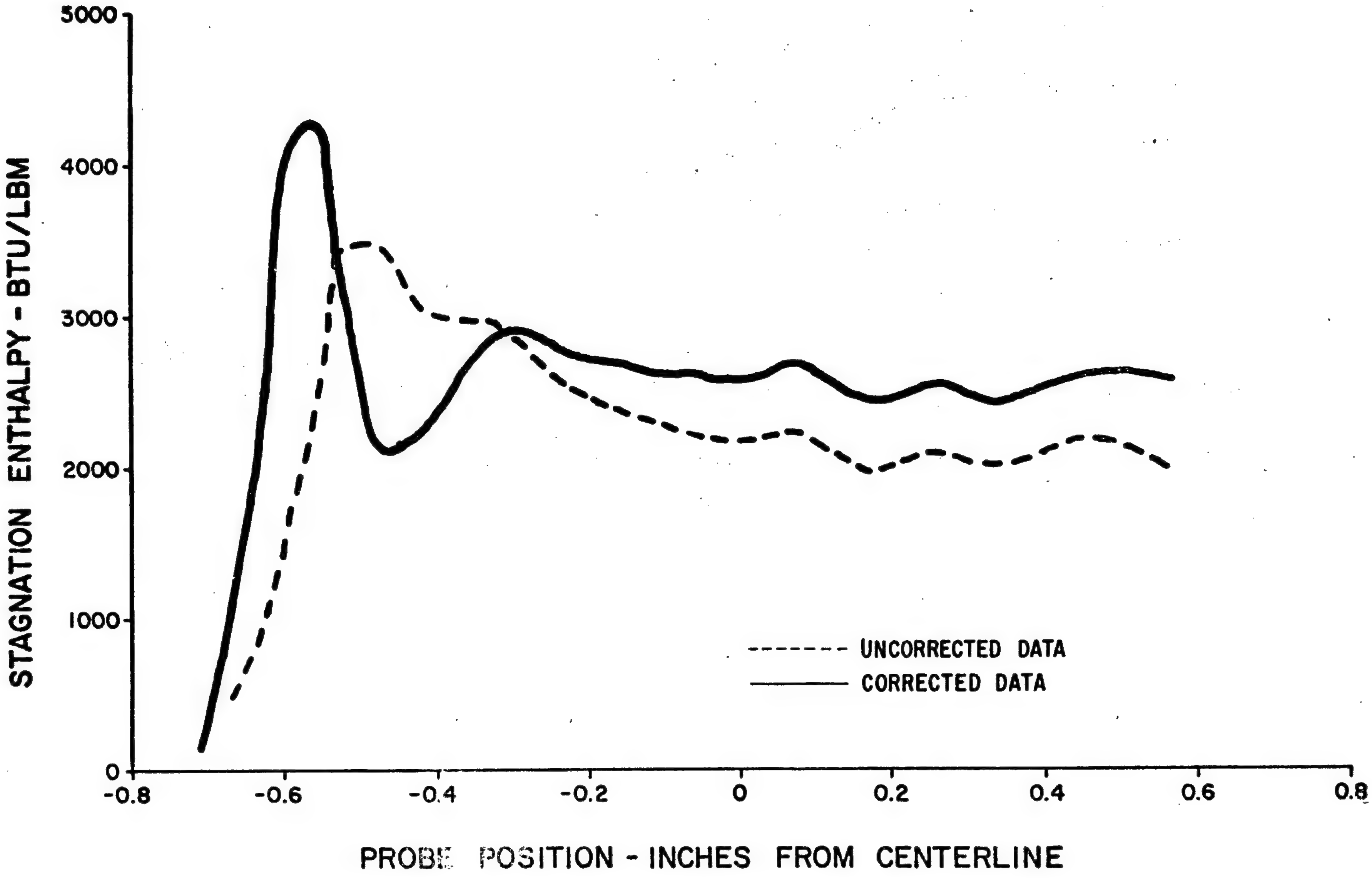

Figure 3a. ENTHALPY PROFILE for RUN 057

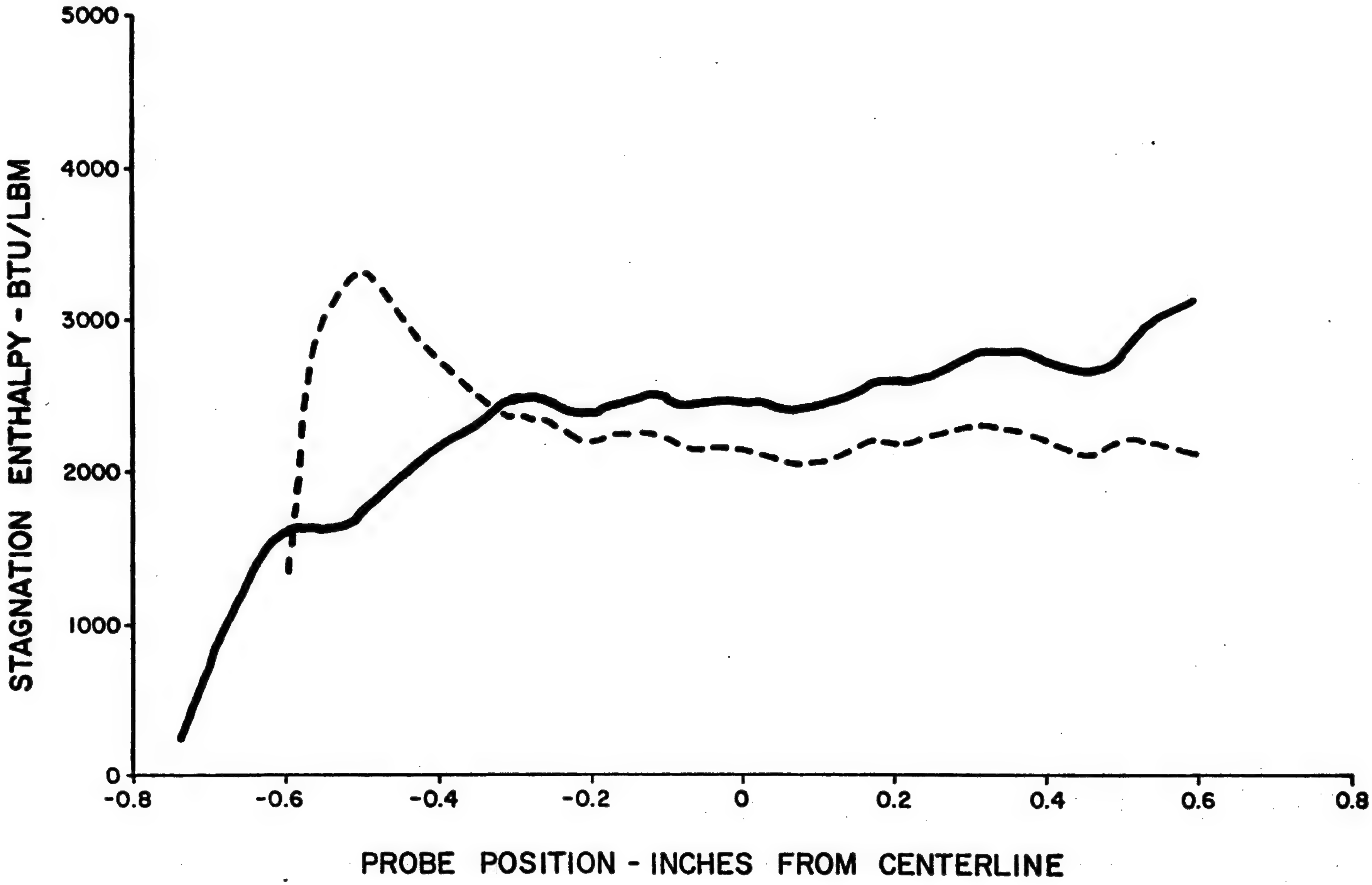

Figure 3b. ENTHALPY PROFILE for RUN 058

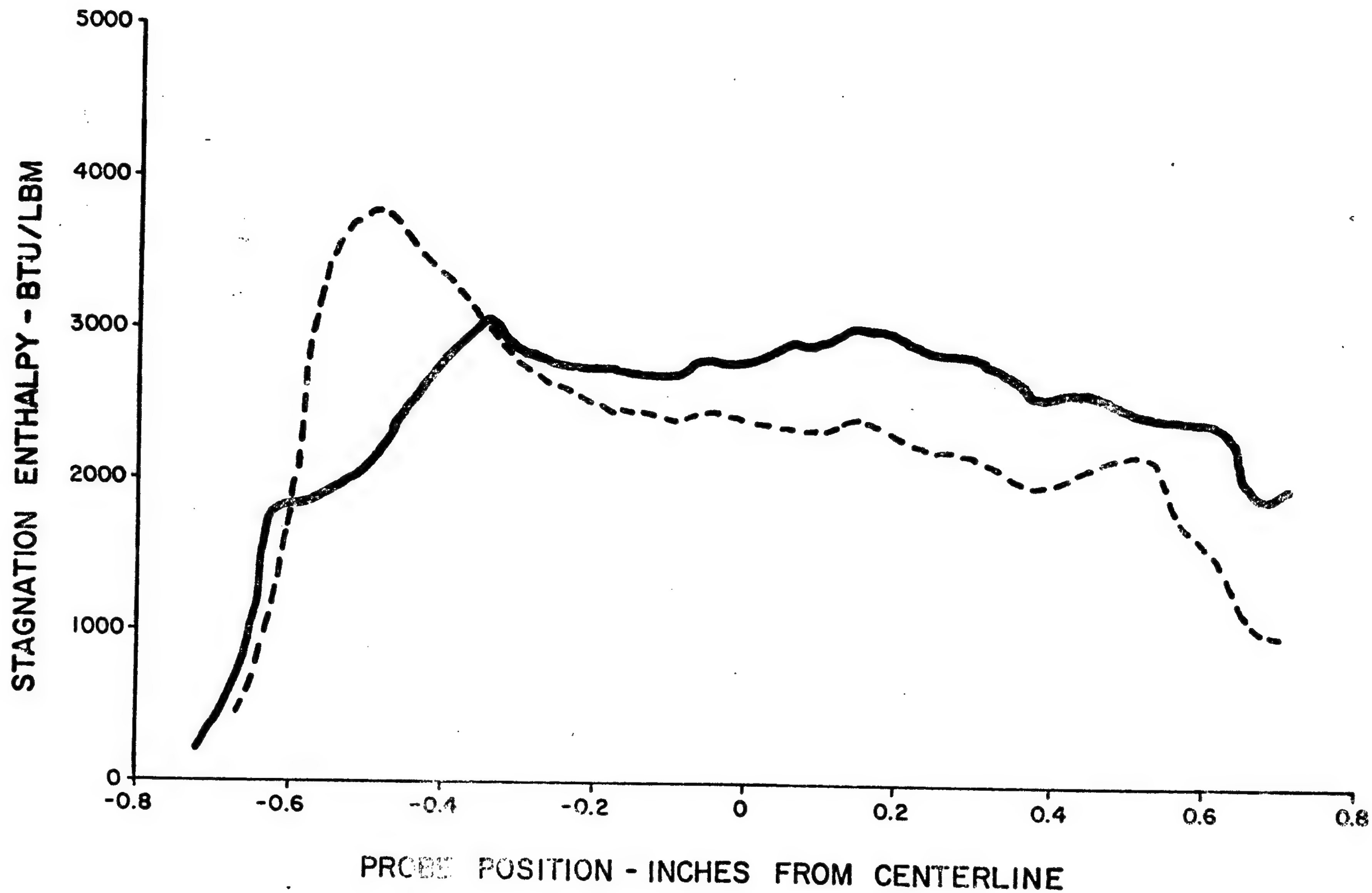

Figure 3c. ENTHALPY PROFILE for RUN 059

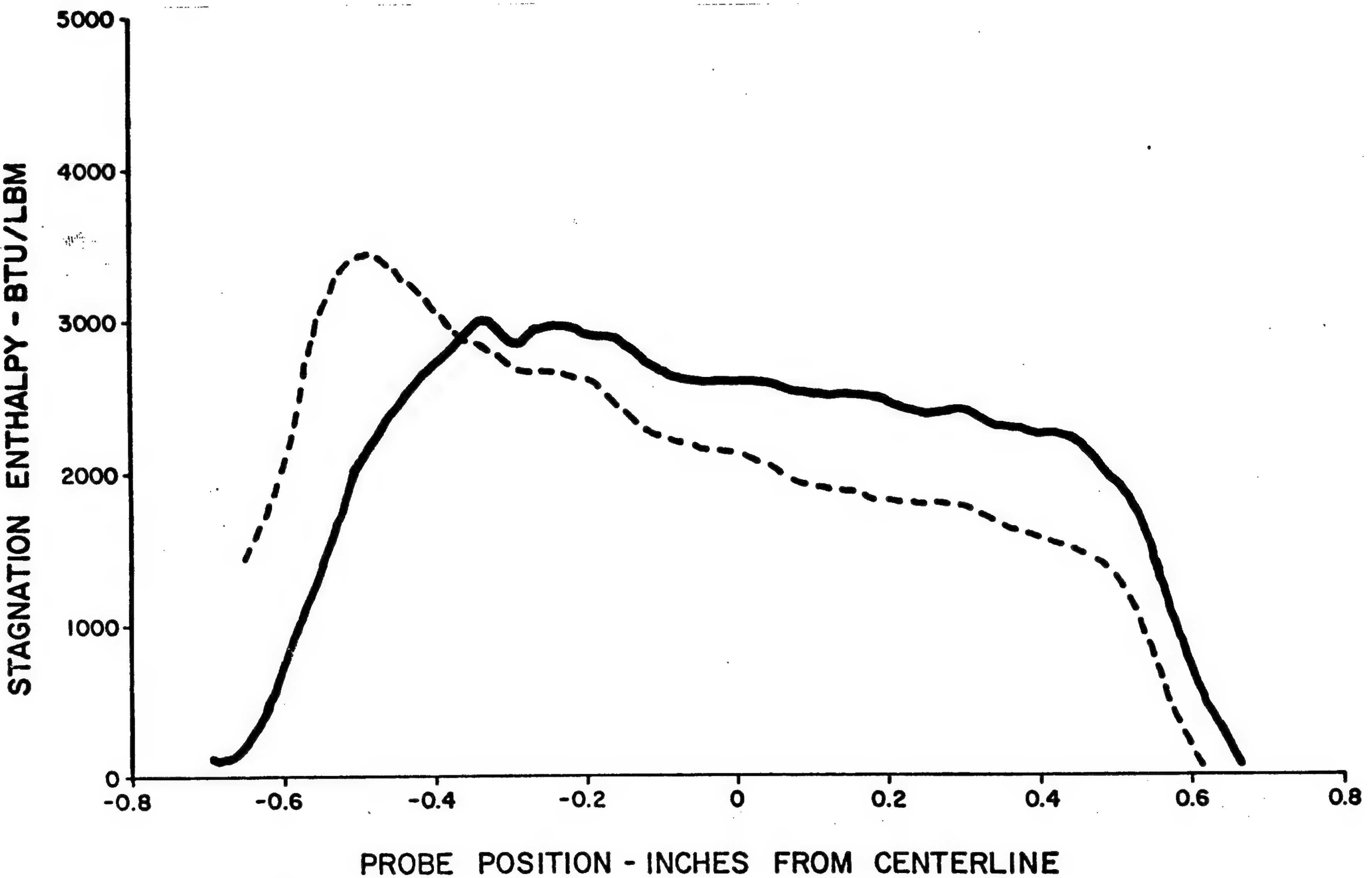

Figure 3d. ENTHALPY PROFILE for RUN 060

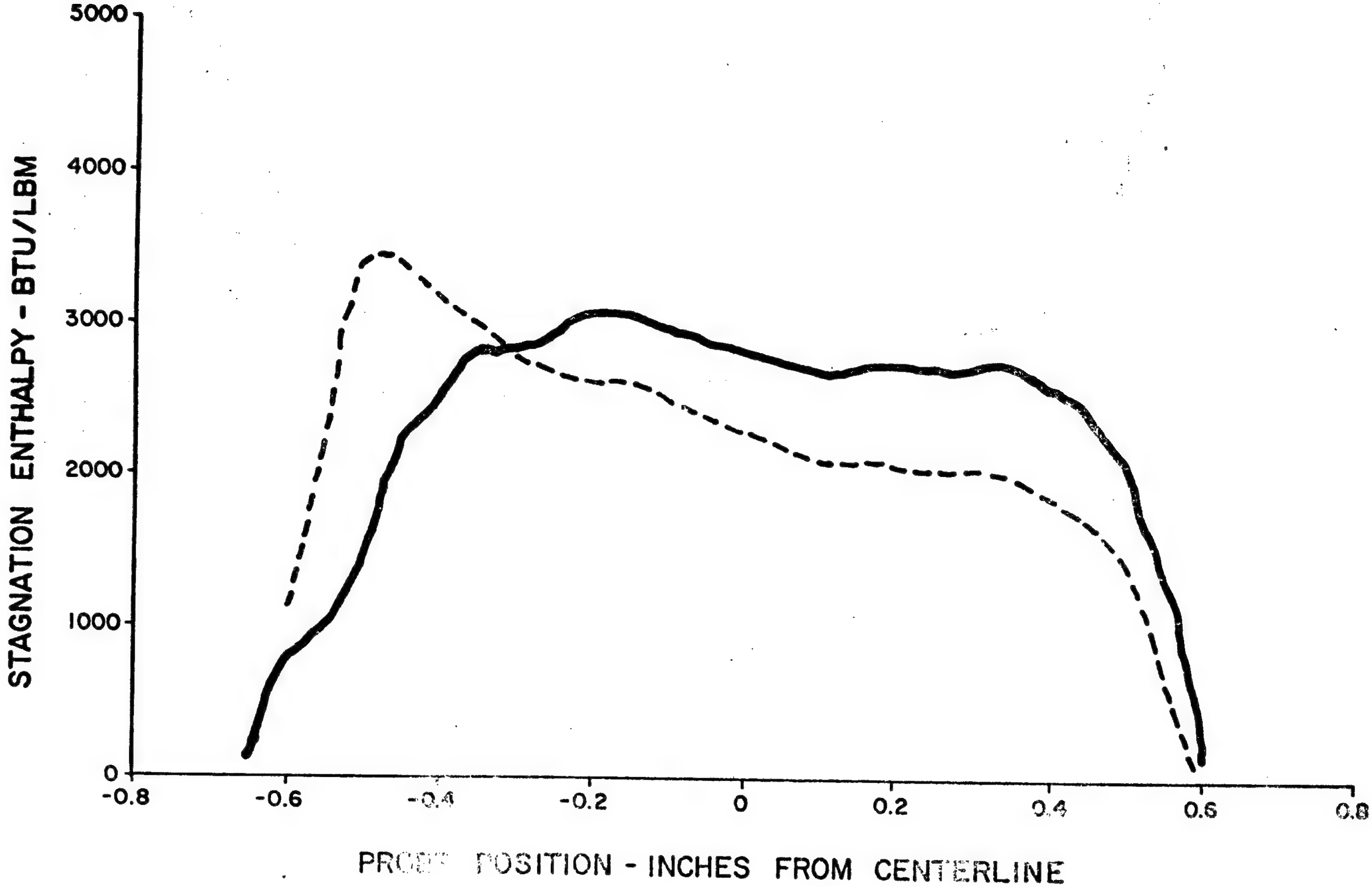

Figure 3e. ENTHALPY PROFILE for RUN 061

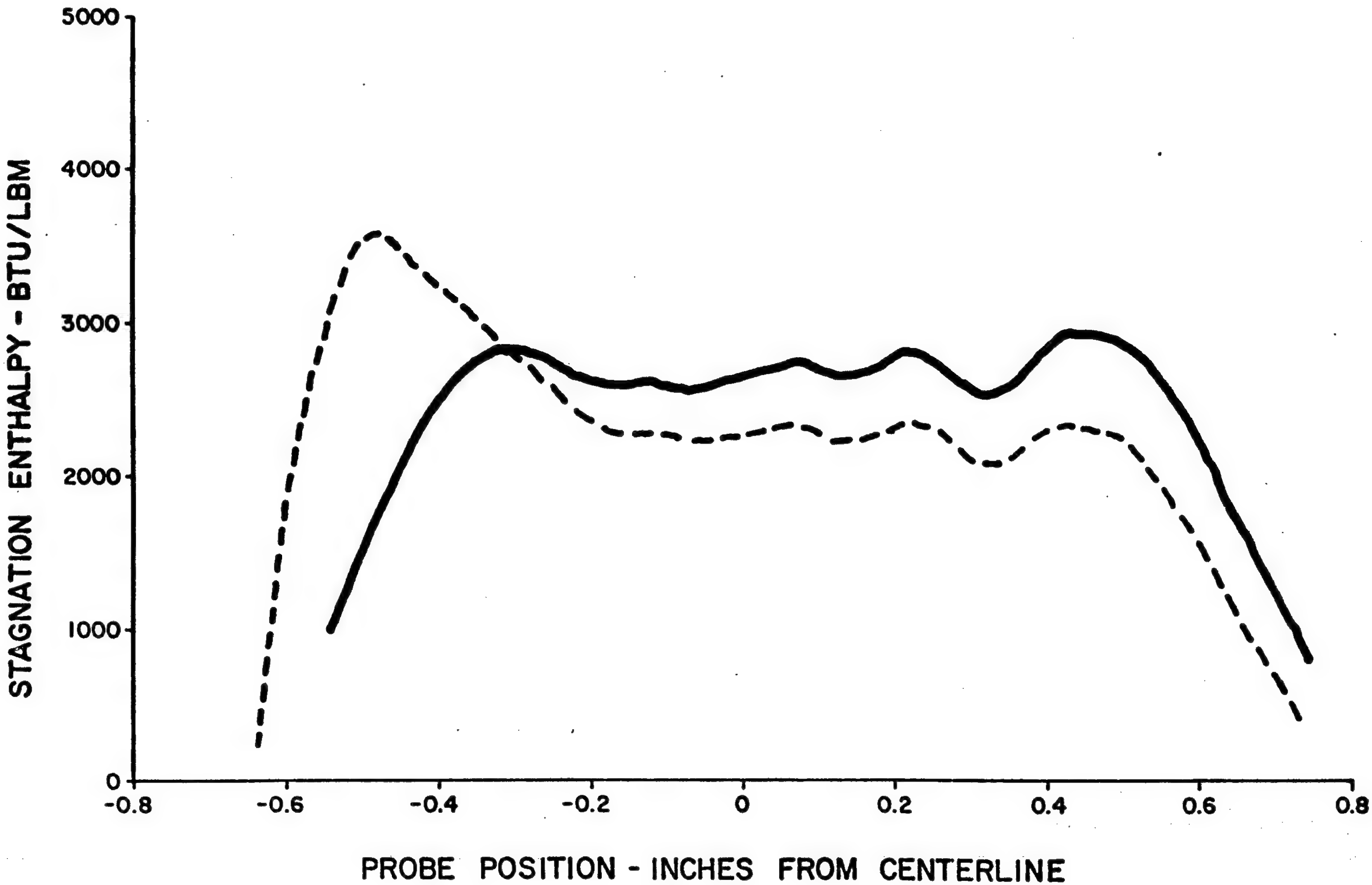

Figure 3f. ENTHALPY PROFILE for RUN 062

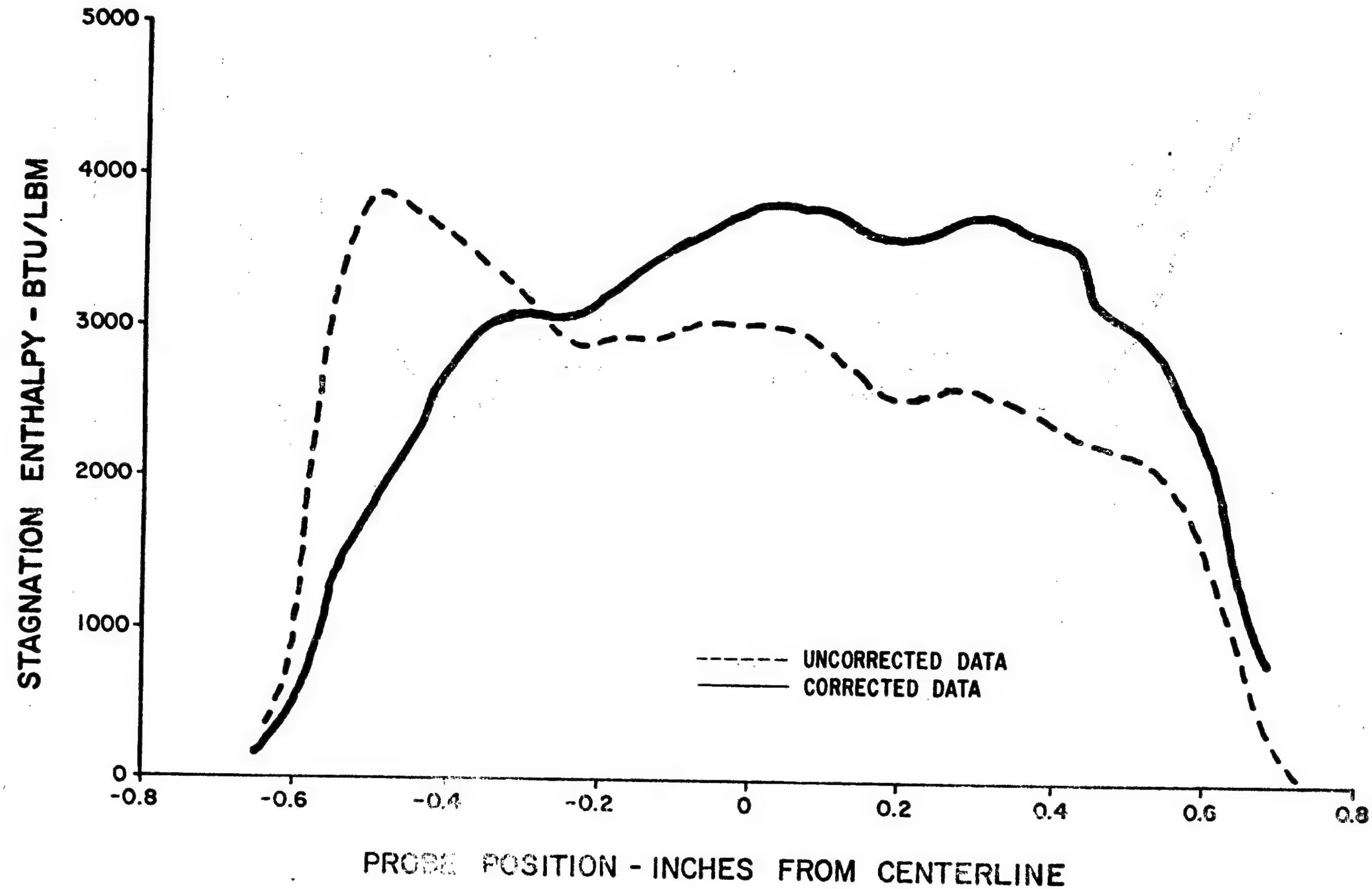

Figure 4a. ENTHALPY PROFILE for RUN 063

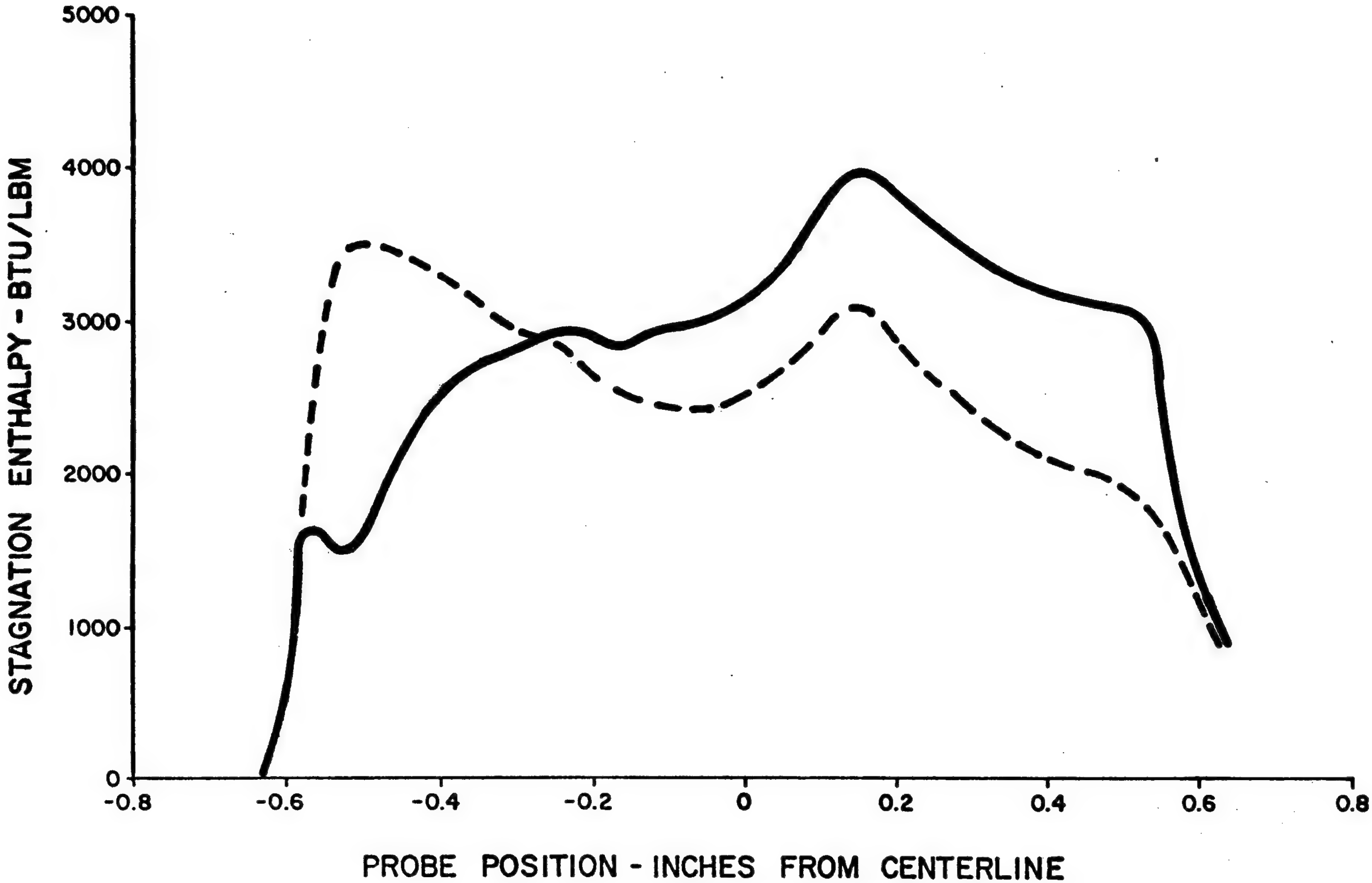

Figure 4b. ENTHALPY PROFILE for RUN 064

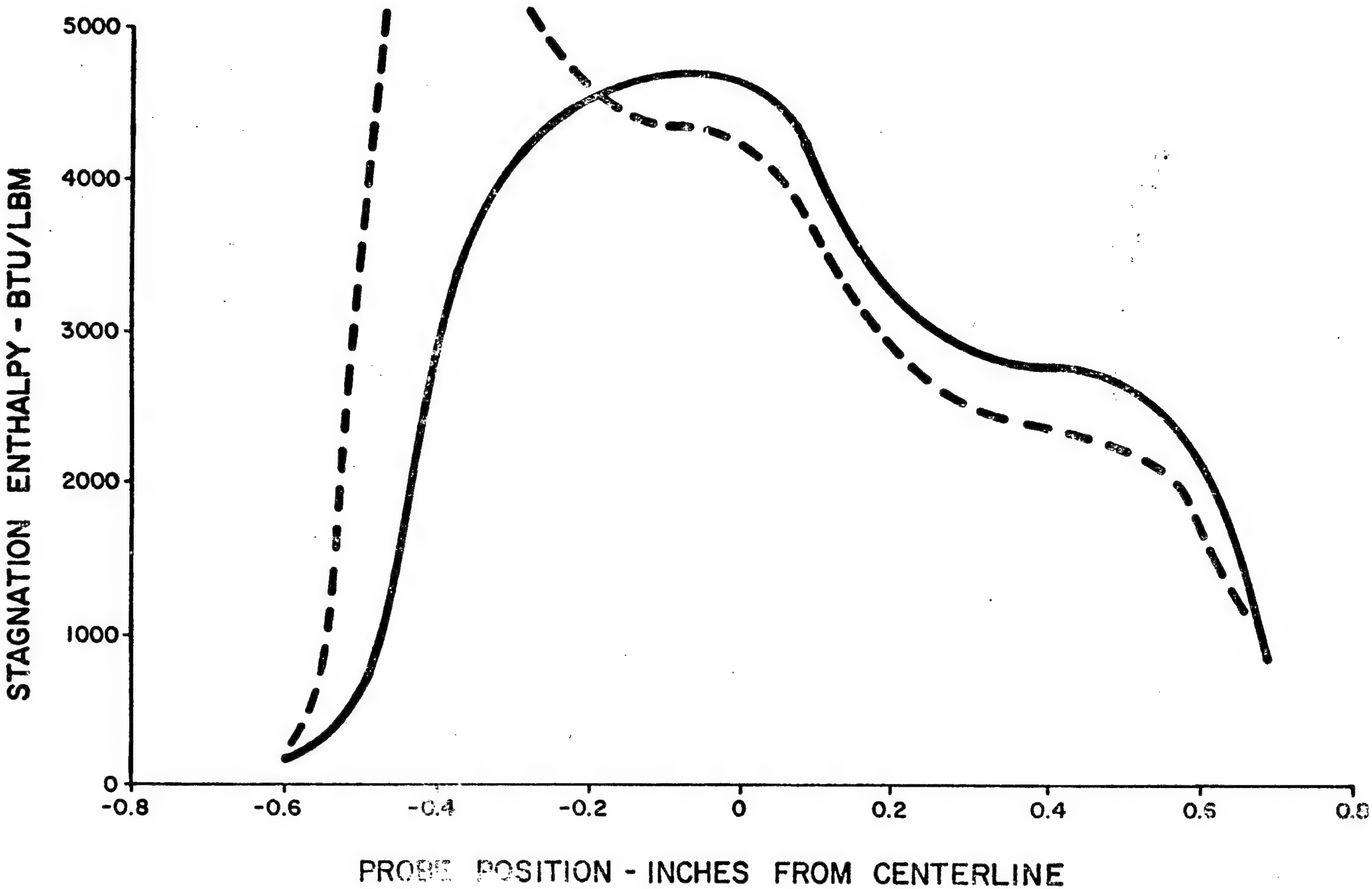

Figure 4c. ENTHALPY PROFILE for RUN 066

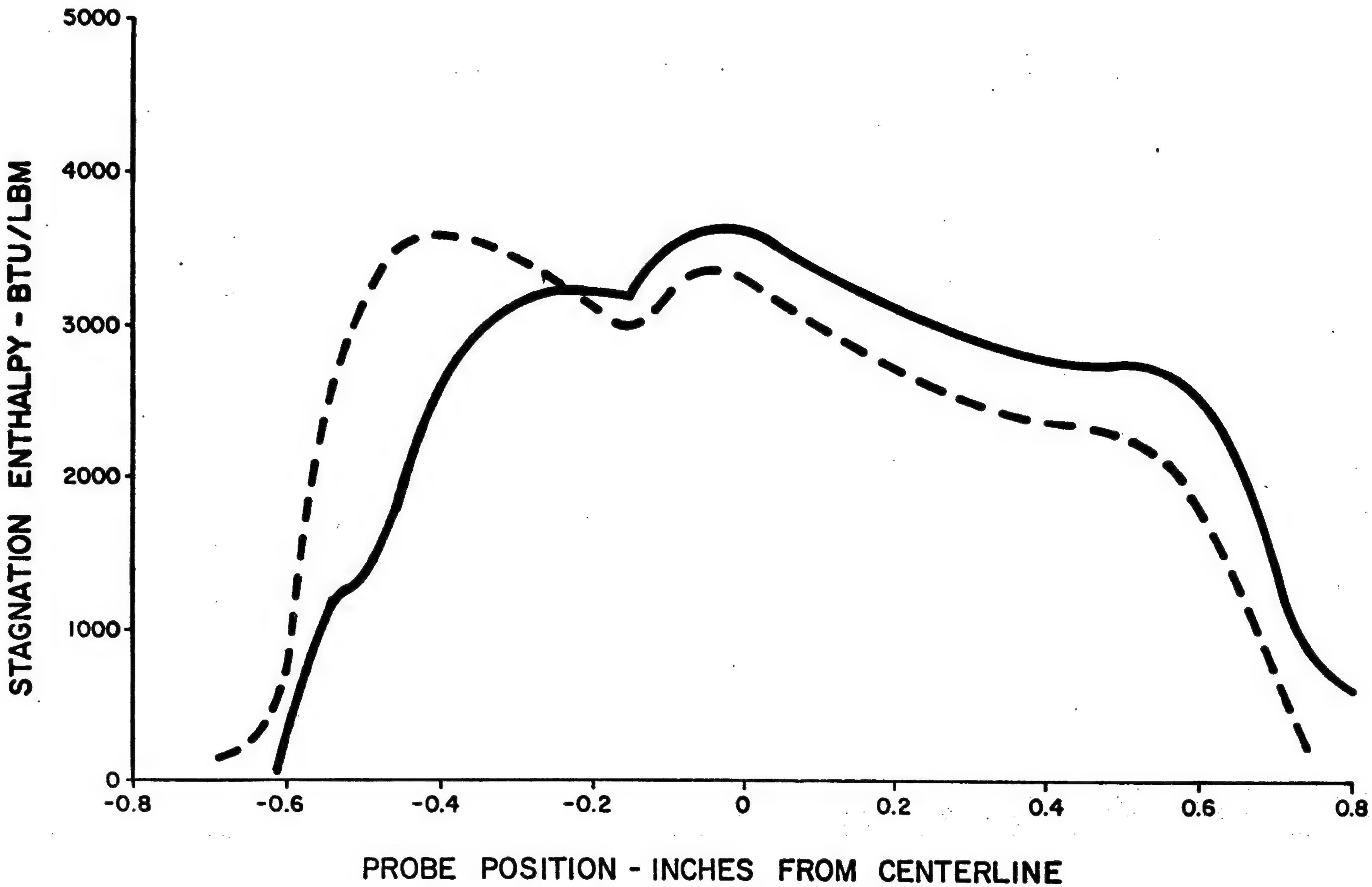

Figure 4d. ENTHALPY PROFILE for RUN 067

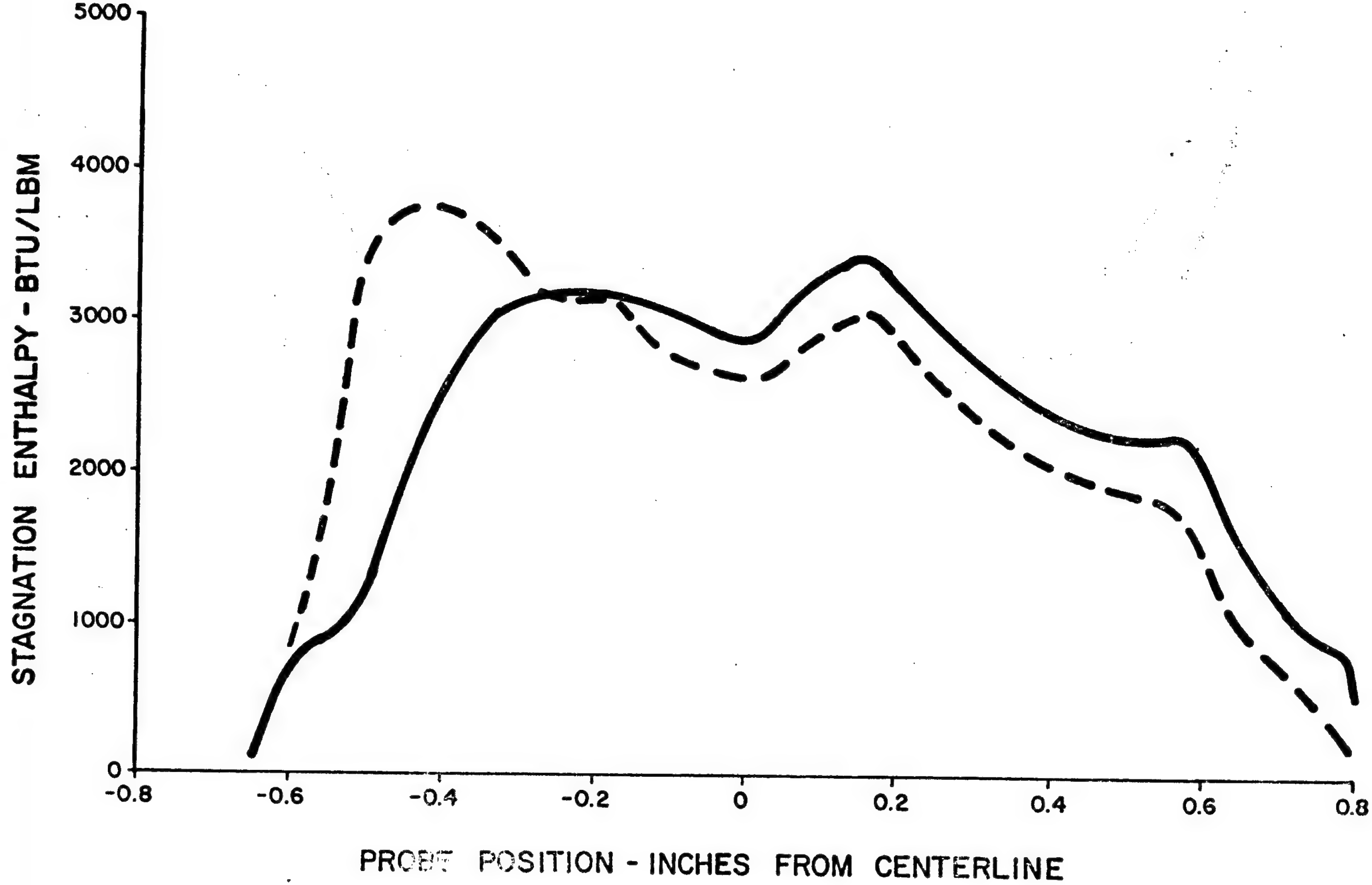

Figure 4e. ENTHALPY PROFILE for RUN 068

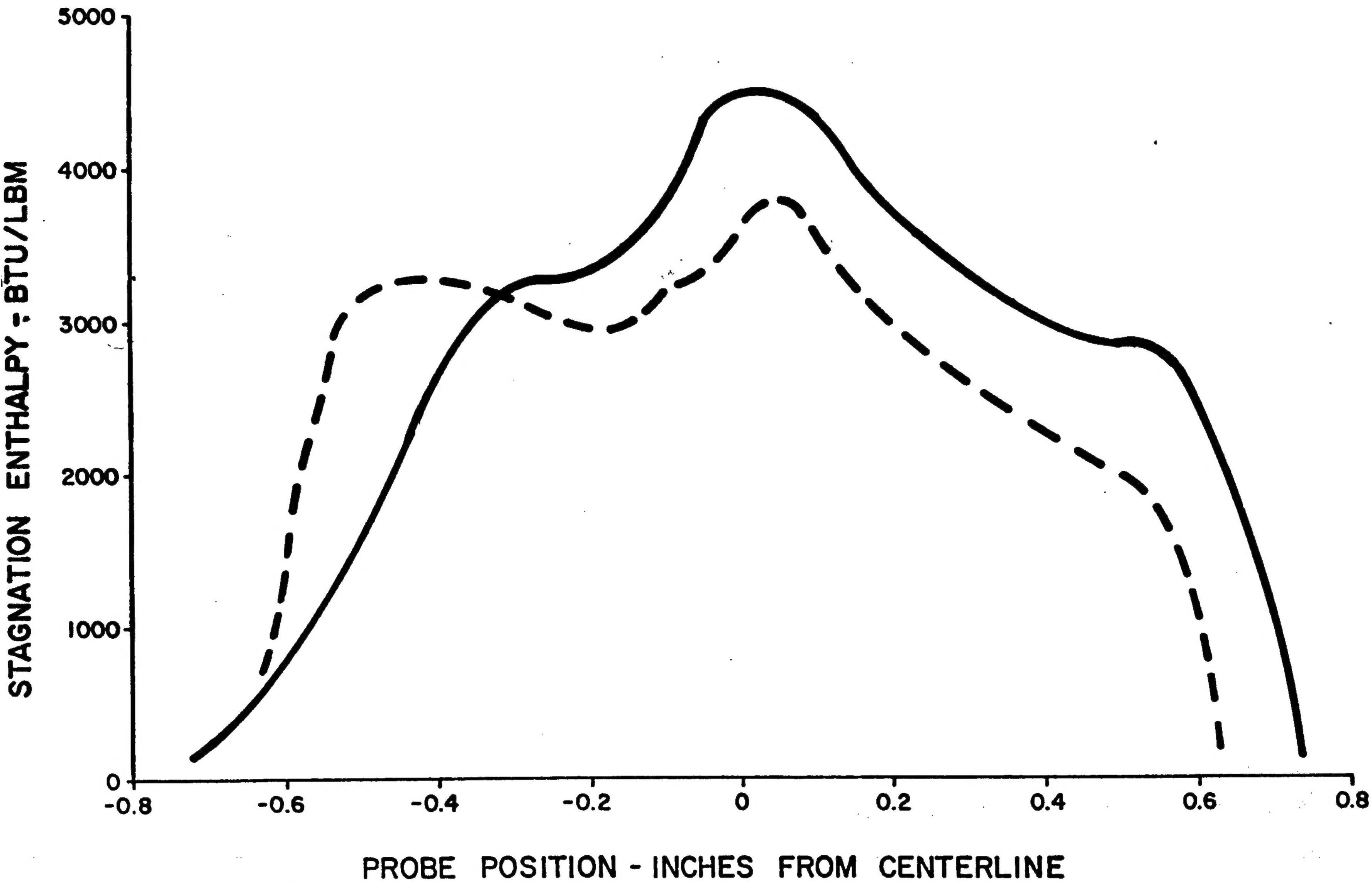

Figure 4f. ENTHALPY PROFILE for RUN 069

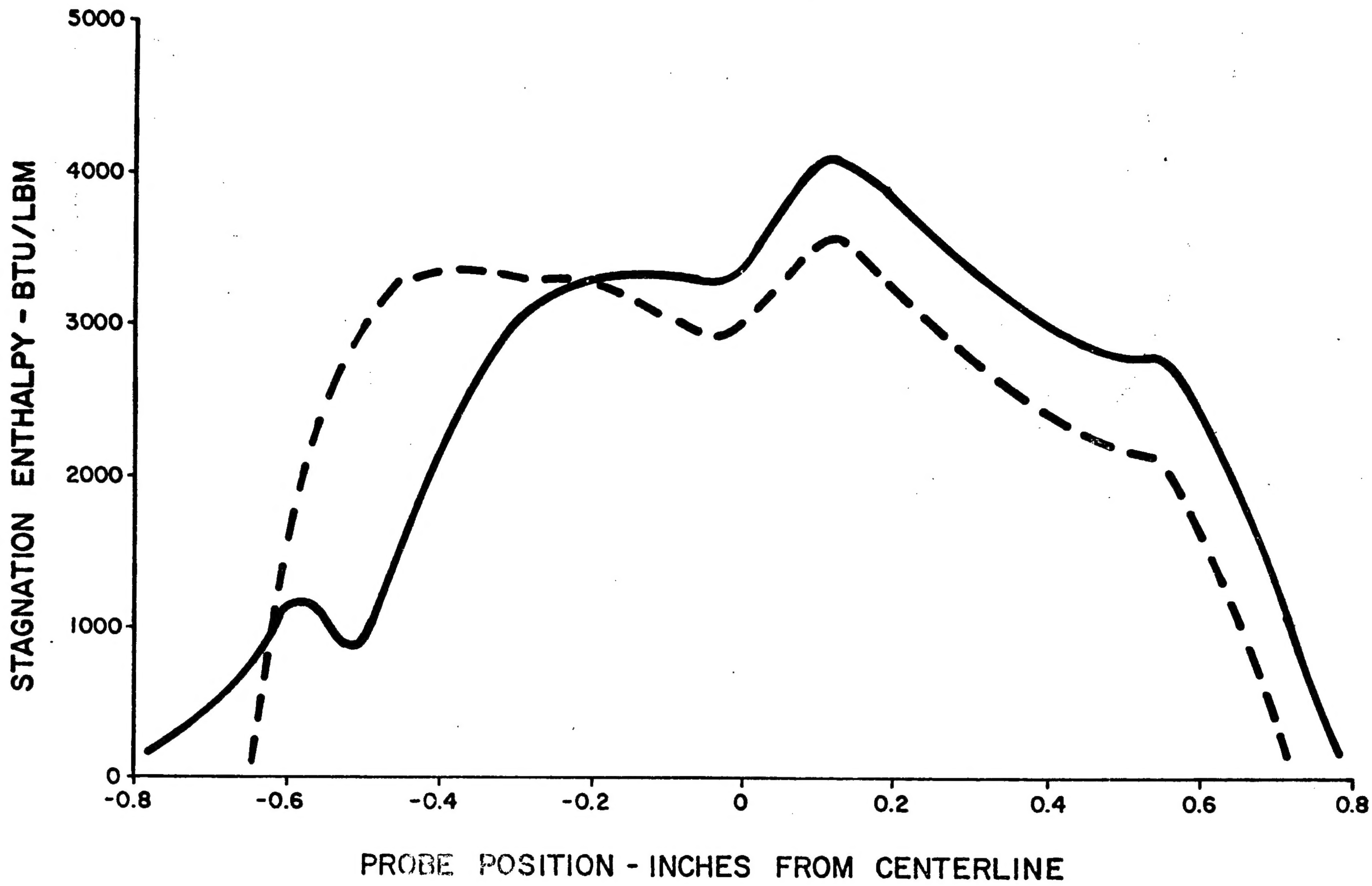

Figure 4g. ENTHALPY PROFILE for RUN 070

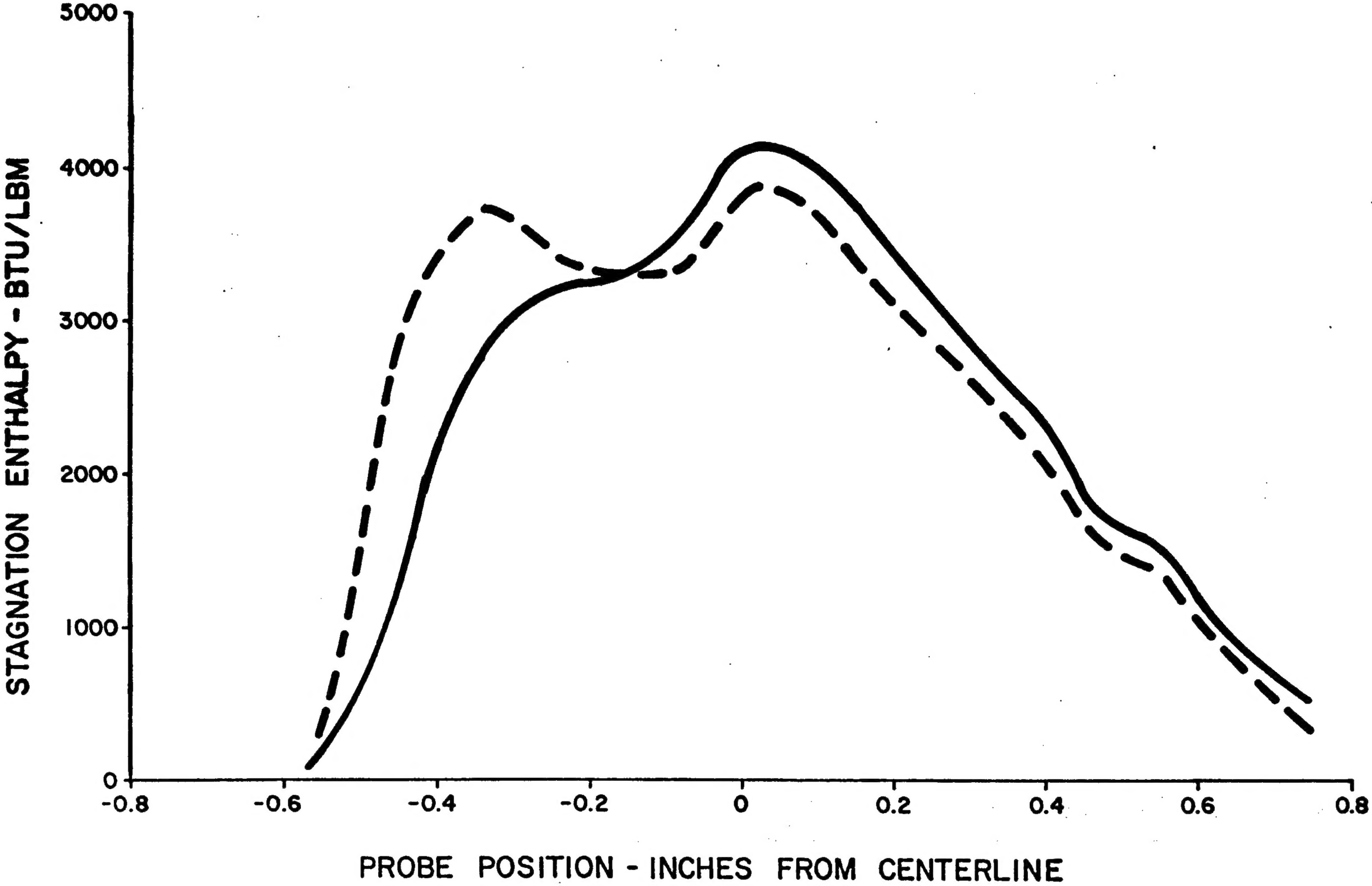

Figure 4h. ENTHALPY PROFILE for RUN 071

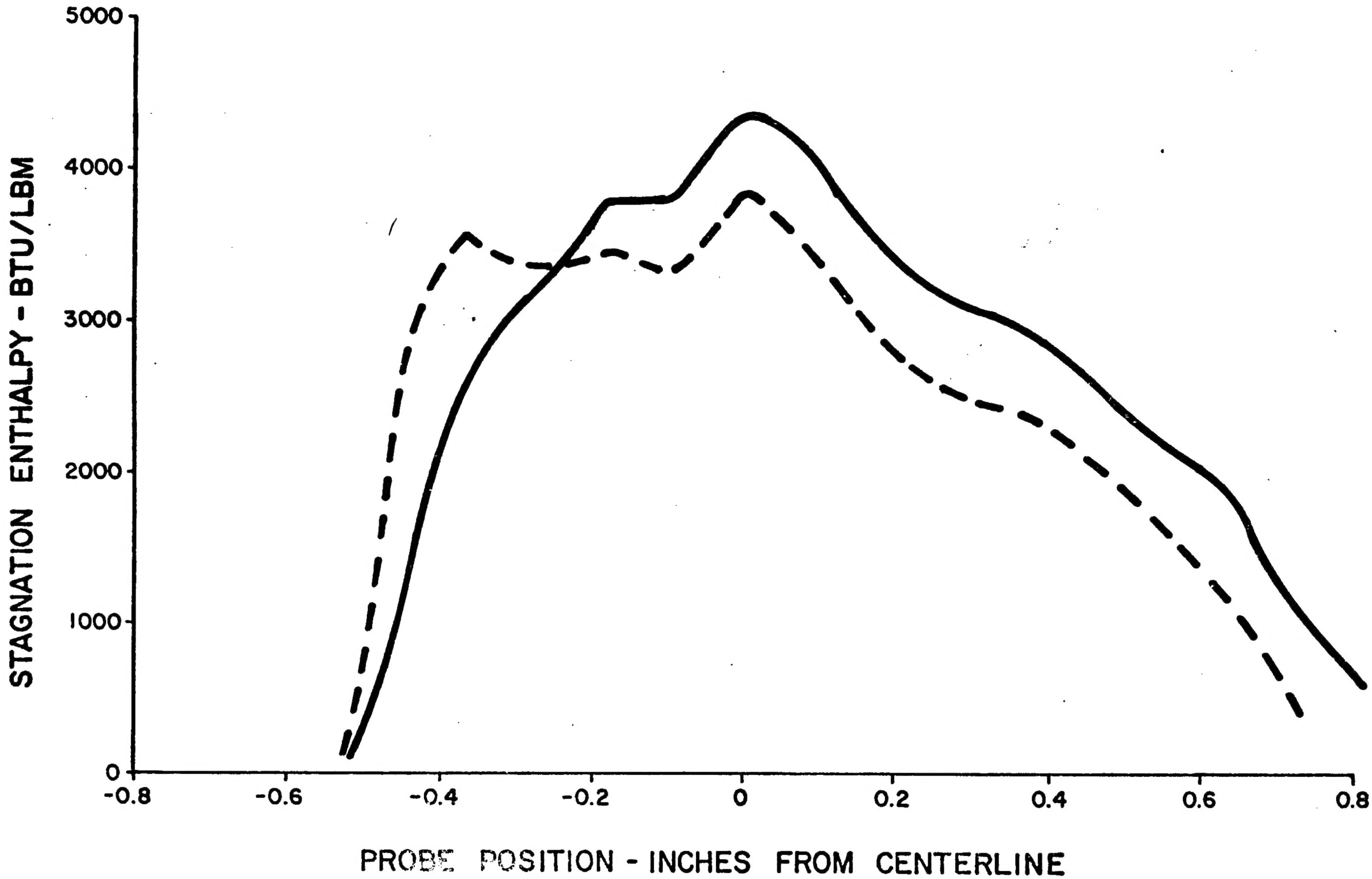

Figure 4i. ENTHALPY PROFILE for RUN 072